Simulation of the motional Stark effect diagnostic gas-filled torus calibration[a)]

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Many motional Stark effect diagnostics around the world make use of a calibration procedure in which the observed neutral beam is injected into a gas-filled torus with known vacuum fields. The instrument is calibrated by reconciling measured angles with vacuum magnetic reconstructions through a range of pitch angles. This *in situ* gas-filled torus calibration most closely approximates the working conditions of the diagnostic and includes effects such as beam and viewing geometries, beam voltages, Faraday and stress induced birefringence (in most cases) of the transmissive optics, as well as the polarimeter response. However, secondary neutrals, produced after ionization then reneutralization of a beam neutral, have been found to contaminate measured angles by emitting Balmer alpha with similar Doppler shifts and Stark polarizations as beam neutrals, but with different polarization angles. Simulation results that show spectral and angle behavior versus calibration parameters such as fill gas pressure will be presented. Data from NSTX and C-Mod will be compared to simulations results. © *2008 American Institute of Physics.* [DOI: 10.1063/1.2969419]

INTRODUCTION

The motional Stark effect (MSE) has become an important instrument for the measurement of the internal magnetic pitch angle profile in toroidal confinement devices. The MSE diagnostic has been installed on a large number of experiments, including TFTR, JET, NSTX, Alcator C-Mod, DIII-D, JT-60U, ASDEX-Upgrade, Tore Supra, and MAST. A common method of calibration used for the instrument is to inject the observed neutral beam into the torus filled with neutral gas, scanning the vacuum field through a series of pitch angles generated using poloidal field coils. While this *in situ* method is a single procedure that can calibrate every channel of a MSE system including all effects of stress and magnetic fields through transmissive optics as well as geometric mapping of Stark electric field angles, unexpected angles, and spectroscopic features have occurred.[1] The most anomalous results have come out of the MSE diagnostic on Alcator C-Mod as shown in Fig. 1.[2–4] These results can now be explained by emission from secondary neutrals resulting from charge exchange by ionized beam neutrals. This work compares measurements from the C-Mod gas-filled torus calibrations with simulations of the secondary neutral emission.

SECONDARY NEUTRALS

After beam neutrals ionize, they become partially confined by the vacuum field. Some beam ion charge exchange with the fill gas in the torus used to excite the beam neutrals for the MSE signal and emit inside the MSE viewing volume. The ions do not slow down appreciably during this process, therefore the secondary neutral emission can have Doppler shifts and Stark splittings comparable to the beam emission and pass through the MSE filter. However, due to the gyromotion during the ion state, the perpendicular velocity component of the secondary neutrals is randomized about the gyro-orbit. This randomizing of the perpendicular velocity component causes the Stark field for the secondary neutral to be in a different direction from the beam except at a single gyrophase, and thus the polarization angle of the $H\alpha$ will be different from the beam. It is in this way that secondary neutral emission can contaminate the MSE calibration.

A three-dimensional code based on first principles has been written to simulate the secondary neutral emission spectrum and its effect on the MSE measured signal. The simulation starts by calculating the ion birth rate density on a toroidal grid. For each grid cell, ions are launched as pseudoparticles weighted by the ion birth rate along their drifting gyrocenter trajectories. Ions are attenuated along their gryocenter trajectory, but using the actual ion path length traveled. Ions are tracked until they have fully attenuated, or more likely, reached the boundary defined at the vacuum vessel surfaces and considered lost. Secondary neutrals from each grid cell are then launched with user specified gyrophase resolution and their emission intensity in MSE viewed grid cells are recorded. Figure 2 shows the birth rate density of secondary neutrals for two comparison cases in Alcator C-Mod. Steady state particle flow continuity is assumed along ion paths and is used to conserve particles. This is an acceptable assumption for this prompt secondary neutral effect because the total lifetime for beam particles inside the vessel is short compared to the MSE measurement time.

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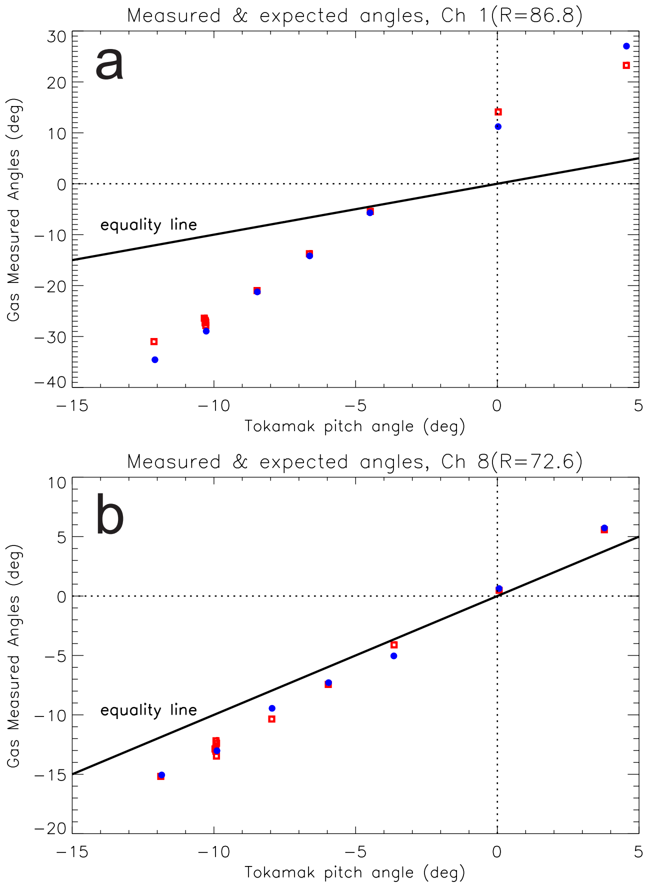

FIG. 1. (Color online) C-Mod measured pitch angles during calibration. Top (a): plasma edge channel. Bottom (b): plasma core channel. Square red points shown are at nominal filter locations while blue circles show effect of a 3.4 Å increase in filter wavelength.

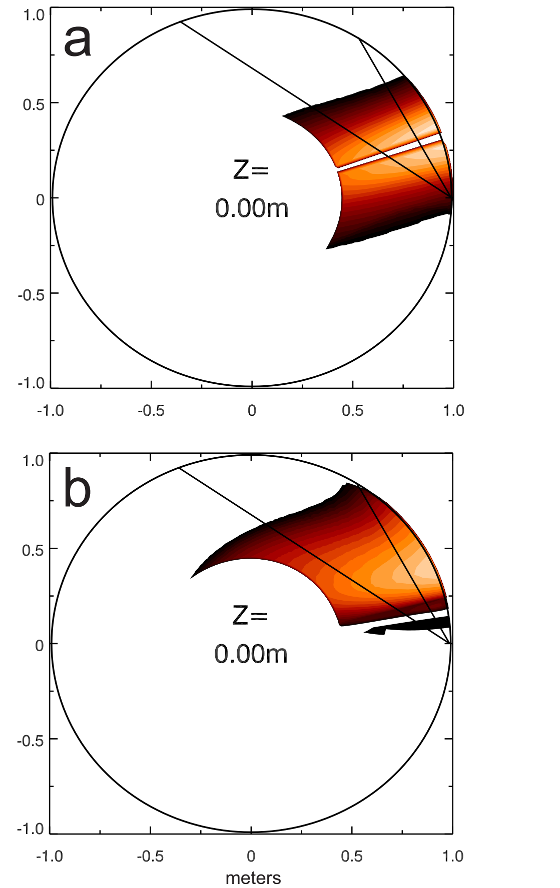

FIG. 2. (Color online) Simulated secondary neutral birth rate density [$m^{-3}\,s^{-1}$] for Alcator C-Mod. Extent of sight lines are shown by lines. Top (a): radial beam at 2 mTorr. Bottom (b): beam tilted at 7° at 0.25 mTorr.

To calculate the observed spectrum, the emission for all beam and secondary neutrals is calculated using the quantum mechanical dipole description for $H\alpha$ in an $E\times B$ field outlined in Ref. 2. Velocity vectors of ions and secondary neutrals are tracked so that the Doppler shift with respect to the MSE sight line, the $E\times B$ Stark splitting, and the polarization direction can be calculated. Since the Stark field for secondary neutrals can have arbitrary direction relative to the MSE sight line the Stark multiplet intensities can be different than beam neutrals. The Stokes vectors from all contributing beam and secondary neutrals are then integrated over the viewed volume for each MSE channel to calculate the observed spectra and the measured polarization angles.

DISCUSSION OF RESULTS

Simulated spectra are shown with a measured spectrum in Fig. 3. For C-Mod, which views red Doppler-shifted and red Stark-split π multiplet lines of the full energy beam component, a telltale signature of secondary emission can be found in the low intensity tail extending far into the blue side of the unshifted $D\alpha$ line, where no emission is expected. Fitting the peaks in the spectrum allowed the beam species neutral fractions to be calculated. Fitted values used in the simulation are full (22%), half (10%), one-third (56%), and 1/18th (14%) (from water) energy.

Despite being able to simulate the intensity of the secondary neutral emission, it is difficult to calculate its net Stokes vector. Calculating the net Stokes vector requires knowledge of the excited state population of the secondary neutrals in the $E\times B$ fields just after charge exchange. Figure 4 shows that for several core channels that view the beam with a significant redshift, the net polarization observed is oriented in the σ direction when assuming a statistical excited state population. This polarization has a linear polarization angle orthogonal from what is necessary to explain measured angles. Furthermore, for the entire array of sight lines with a continuous range filter passbands, the net polarization of the secondary neutrals will go from net σ through zero, then net π polarization when assuming a statistical excited state population. However, all sight lines on C-Mod show π polarized contamination, suggesting that the secondary population is not statistically populated. This should not be surprising; however, since Levinton has measured nonstatistical populations for beam neutrals[1] that had an increased fraction of π light relative to σ. In the simulation, in order to satisfy the condition that all sight lines observed π polarized light, the $[\sigma_0:\sigma_1:\pi_2:\pi_3:\pi_4]$ line ratio was adjusted to be [1.00:0.47:1.14:1.47:1.85].

Discrepancies between expected and observed angles were reproduced in simulation results after adjusting for the population states. Figure 5 compares the simulated pitch angles with expected angles for two C-Mod MSE sight lines

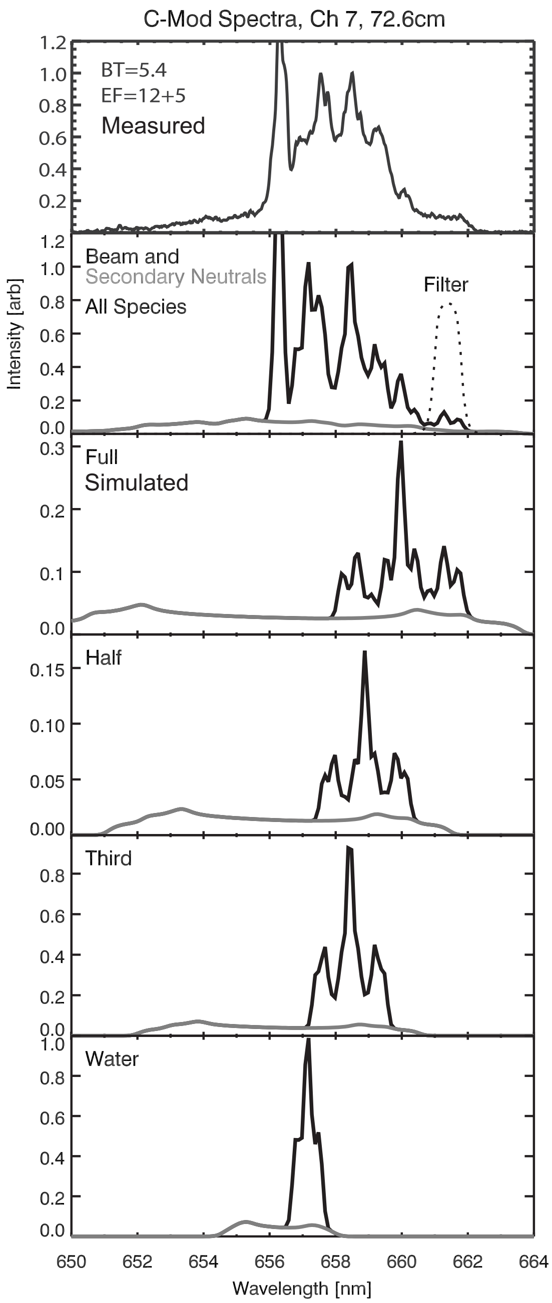

FIG. 3. Measured (top panel) and simulated spectra (remaining panels) of beam and secondary neutral emission. The spectra of each beam species component in the simulations are shown.

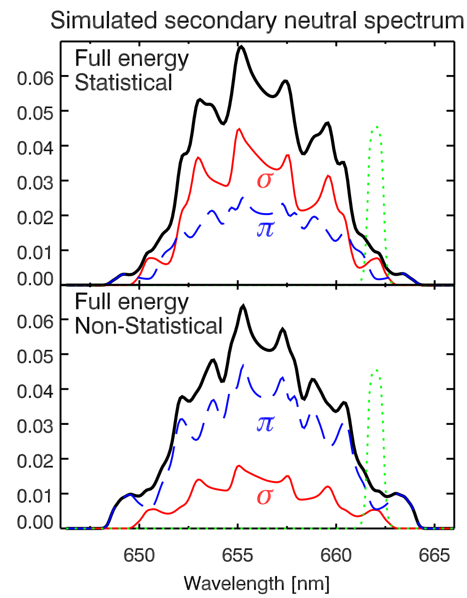

FIG. 4. (Color online) Secondary emission spectra using statistical populations show wavelength regions with net polarizations ranging from σ to π polarization. Because all sight lines on C-Mod observed net π polarization secondary emission, a nonstatistical population was assumed in the simulation.

near the plasma magnetic axis and near the plasma edge. Due to the geometric projection factor, the apparent error in the edge channel appears dramatically worse. These results are consistent with the measured effect of secondary neutrals shown in Fig. 1.

Similar to the beam emission, the secondary neutral emission shown in Fig. 4 varies in polarization fraction, polarization angle, and filtered intensity with central filter wavelength. However, unlike emission from the monodirectional beam, for which the Doppler and Stark splitting are well defined for each emitting atom, the secondary emission is composed of a distribution of Doppler shift and Stark splittings, making the linear polarization angle a function of wavelength even within just π and σ emissions. These effects also cause the net secondary emission linear polarization angle to be sensitive to the beam species mix for cases where Doppler-shifted half and third energy secondary species can also pass through the MSE filter.

To reduce the effect from secondary neutral emissions, the C-Mod diagnostic neutral beam was tilted about 7° from a pure radial direction. Secondary neutral emission is maximized for radial beam injection because there is no parallel velocity component to carry the ions out of the MSE viewing volume prior to charge exchange, only the very slow ∇B and curvature drifts. By tilting the beam, there is a convective term in particle continuity and the ratio of beam to secondary emission becomes a function of fill gas pressure. By increasing the mean free path of the ion so that it flows out of the MSE viewing volume before charge exchanging, one can minimize the effect of secondaries, as shown in Fig. 6, The

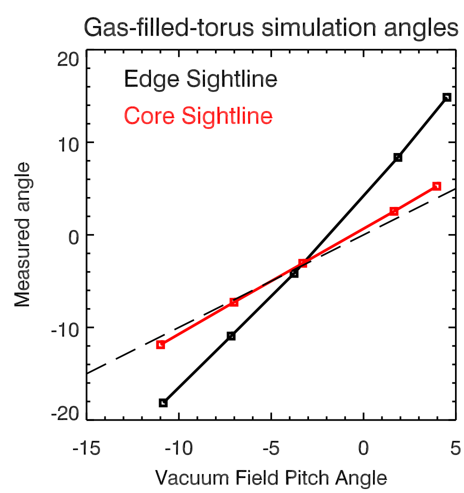

FIG. 5. (Color online) Simulated effect on pitch angle measurement agrees with measured results shown in Fig. 1.

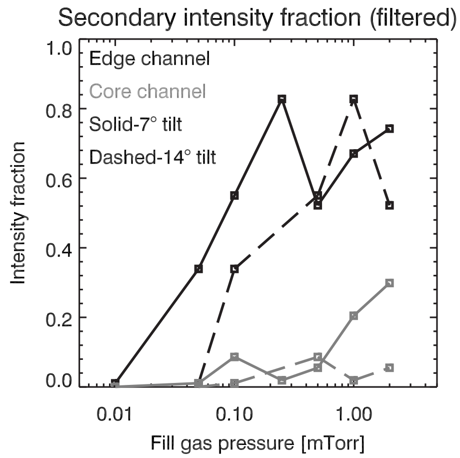

FIG. 6. Relative intensity of secondary emission to beam emission for C-Mod for an edge and core channel at two beam tilt angles. The edge channel suffers more primarily because it observes secondary emission originating from the one-third energy beam species.

simulation shows that at a 7° tilt angle, the fill gas pressure must be reduced to 0.01 mTorr before secondary emission is reduced to a level to allow for pitch angle calibration. However, since reducing the fill pressure also decreases the MSE beam signal, this may not be a useful operating point. By tilting the beam further, e.g., to 14°, C-Mod would be able to calibrate at 0.05 mTorr. It is interesting to note that this is the fill pressure that NSTX uses for its calibration, viewing a tangentially injected beam.

CONCLUSION

A simulation of the secondary neutral emission for the MSE gas-filled torus calibration has quantitatively matched experimentally measured pitch angles and spectra. The simulation has shown that the complexity of the secondary neutral spectrum causes the measured MSE pitch angles to be sensitive to the beam species mix, spectral filter tuning, and fill gas pressure as well as beam injection angle.

The complexity of the secondary neutral spectra suggests that the effect cannot be calculated and subtracted from measured angles, but rather should be avoided during the calibration. Successful gas-filled torus calibrations, such as at NSTX, use very low pressure fill gas with a toroidally injected beam. On NSTX, for example, the fill gas is performed at 0.05 mTorr. Despite the complexity of the secondary emission, finding it should be a simple matter of changing the fill gas pressure during the calibration. The measured pitch angle should not vary with gas pressure if the measurement is not contaminated by secondary neutral emission.

ACKNOWLEDGMENTS

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